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Abstract

This note investigates the impact of (international) technology transfer on optimal pollution taxation. To use a patented pollution abatement technology, the polluters subject to the emissions tax only pay *fixed* license fees to an (international) eco-industry (whose profits are shared among national and foreign suppliers). The second-best emissions tax is shown to decrease as the *exogenous* share of imported technology increases. When the domestic polluting industry is imperfectly competitive, this tax is *always* lower than the marginal damage. In contrast, when the polluting industry is perfectly competitive, the second-best emissions tax is lower than the marginal damage only in the case of *incoming* technology transfer. If the technology is transferred domestically, the second-best emissions tax is equal to the marginal damage. These results contrast with the literature on the impact of market power in the eco-industry on optimal policy design, initiated by David and Sinclair-Desgagné (2005).

JEL Classification: H23, L13, Q58.

Key words: Pigouvian Taxes, Eco-Industry, Technology Transfer, International Trade.

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1 Introduction

Sound environmental policies take into account various complex economic factors. For example, to correct a pollution externality, the so-called Pigouvian tax rule prescribes to levy a per unit emissions tax equal to the marginal damage of pollution.[1] In the absence of other distortions in the economy, applying this rule moves the competitive equilibrium of the economy to the social optimum. In second-best environments, however, this prescription must be amended. For instance, the presence of *market power in a polluting industry* might justify to levy an emissions tax *lower* than the marginal damage, so as to mitigate further distortion in the output market (see e.g., Buchanan (1969) and Barnett (1980)).

Ever increasing ecological awareness and stricter environmental regulations worldwide have given rise to a sizeable market for environmental goods and services (EGS) supplied by a specialized *eco-industry* whose products range from end-of-pipe equipment pollution control and clean-up technologies, to recycling and professional services. In 2010 for example, the European eco-industry's turnover was estimated at around EUR 349 billion, representing roughly one third of a global market estimated at EUR 1.15 trillion. While environmental *services* such as contaminated soil and groundwater remediation, solid waste management and waste water treatment represent the bulk of this business, the licensing of patented abatement *technologies* also generates substantial revenues. Moreover, while much of that turnover already resulted from international trade of EGS, ongoing discussions at the World Trade Organization include negotiations to remove the remaining trade barriers preventing their free flow.[2]

Recently, a series of papers have revisited the Pigouvian tax rule to take into account the impact of market power in the eco-industry on optimal policy design *in a closed economy*.[3] In their pioneering work, David and Sinclair-Desgagné (2005) show that in the presence of market power on the supply side of EGS, the second-best emissions tax to levy in a *competitive* polluting industry *exceeds* the marginal damage of emissions. The intuition behind this result can be understood as follows. The exercise of market power

[1]The marginal damage of pollution depends on the estimated impact that environmental degradation has on various factors such as health, capital and labor productivity, etc. See e.g., Muller and Mendelsohn (2007).

[2]See e.g., OECD (2001) for a tentative definition of the eco-industry and see an EC study at http://ec.europa.eu/environment/enveco/jobs/.

[3]See for example, David and Sinclair-Desgagné (2005, 2010), Perino (2010), Canton et al. (2008) and Nimubona and Sinclair-Desgagné (2013).

in the eco-industry leads to EGS priced above their marginal cost. This markup distorts the polluters' abatement incentives downward. Therefore, *when the emissions tax is equal to the marginal damage*, the inadequate supply of (socially desirable) EGS moves the economy away from the second-best equilibrium. To encourage more abatement and thereby mitigate this deadweight loss, the emissions tax must be raised above the Pigouvian level.

Building on this work, Canton et al. (2008) and Nimubona and Sinclair-Desgagné (2013) extend the analysis to the case where *both* the polluting industry and the eco-industry are imperfectly competitive.[4] What these papers essentially suggest is that the comparison between the optimal tax and the marginal damage depends on both industries' relative market power: a relatively more concentrated polluting industry (resp. eco-industry) tilts the balance towards a lower (resp. higher) emissions tax. Importantly, however, underlying these results are two key assumptions which, in the light of available evidence on the eco-industry, deserve further examination. One concerns the emissions tax-induced redistribution of rents *within* the economy. The other relates to the definition of environmental goods and services.

Firstly, since all these papers assume that the eco-industry's profits *entirely* contribute to *domestic* welfare, the adverse impact a higher emissions tax might have on polluters and consumers' surpluses is somehow mitigated by an increase of these profits.[5] Yet, in many countries polluters rely on imported EGS. In such cases, part of the eco-industry's profits "leaks" outside the boundaries of the domestic economy. This raises the question as to how the possibility of international trade of EGS does influence optimal environmental regulation.

Secondly, in all these models EGS are subject to linear pricing. Consequently, when the eco-industry is imperfectly competitive, polluters have to bear a positive markup for each unit of EGS they purchase. While the assumption of linear pricing is certainly relevant for end-of-pipe environmental *services* or environmental inputs to the polluters' abatement processes, it might be less applicable to many environmental equipments like abatement *technologies* (e.g., air pollution control devices such as scrubbers, carbon capture technologies,

[4] David and Sinclair-Desgagné (2005) consider a Cournot oligopolistic eco-industry supplying EGS to a competitive polluting industry subject to environmental regulation. Canton et al. (2008) consider oligopolistic polluters taking the price of EGS as given, while Nimubona and Sinclair-Desgagné (2013) introduce monopsony power on the demand side of EGS.

[5] This line of reasoning is reminiscent of that suggesting that economic losses due to enforcement of stringent environmental policies would be partially offset by the creation of "green jobs" in the eco-industry (see e.g., Martinez-Fernandez et al. (2010)).

filters, etc) likely to be implemented in polluting industries.[6]

The present paper revisits the Pigouvian tax rule, taking into account the possibility of international trade of EGS. It thus ties in two strands of the literature. First, this paper contributes to the aforementioned literature by extending previous analysis to the case of abatement *technologies* (or EGS subject to nonlinear pricing as opposed to environmental *services* subject to linear pricing) and the possibility of *international* technology transfer. In line with conventional wisdom suggesting that governments whose polluters rely on imported EGS are less inclined to enforce stringent environmental policies, the welfare-maximizing emissions tax to be levied in a *domestic* polluting industry is shown to decrease as the foreign share of the eco-industry's profits increases.

Second, this paper also relates to the literature on strategic environmental regulation in open economies investigating the potential use of environmental regulations to achieve competitive advantages in international markets.[7] Pointing that governments might be tempted to use environmental policies strategically to serve rent-shifting objectives (e.g., by setting the emissions tax or environmental standards differently of what they would have done in a closed economy), this literature however generally concludes that environmental policies are in fact poor alternatives to existing industrial policies (see e.g., Barrett (1994)) and, as such, are therefore unlikely to be manipulated to gain competitive advantages. In contrast to that literature, the market share of foreign ESG suppliers is *exogenous* to the domestic environmental policy.

In our model, to abate their desired amount of pollution, the polluters equipped with an abatement technology incur only the associated operational costs. However, adopting a patented abatement technology entails the upfront payment of fixed license fees to the technology supplier, which by definition (of patents) is endowed with some monopoly rights over the use of its technology. First, the welfare-maximizing emissions tax is derived for an imperfectly competitive polluting industry, as in Canton et al. (2008). Then, a perfectly competitive polluting industry as depicted in David and Sinclair-Desgagné (2005) is approached by letting the price elasticity tend to infinity. In contrast to these papers, however, the focus here is on environmental

[6]Moreover, insofar as services are provided on a bilateral contractual base, it seems more natural to think of EGS suppliers' market power as their ability to extract much rents from their customers with efficient bilateral contracts than as their ability to charge a markup on units of EGS they supply.

[7]See e.g., Barrett (1994), Hamilton and Requate (2004), Greaker and Rosendahl (2008).

equipment such as end-of-pipe pollution abatement technologies.

Our analysis suggests that even in the absence of economic distortions due to the exercise of market power in either industry, international rent-shifting motives might call for departing from the Pigouvian tax rule. In the case of technology transfer, the emissions tax that maximizes domestic welfare *never* exceeds the marginal damage and decreases as the extent of *imported* technology increases. When the polluting industry is imperfectly competitive the second-best emissions tax is always lower than the marginal damage. In contrast, when the polluting industry is perfectly competitive, the second-best emissions tax is lower than the marginal damage only in case of technology *import*. If the technology is transferred domestically, the second-best emissions tax is equal to the marginal damage.

The intuition behind these results can be explained as follows. First, observe that, essentially, an emissions tax policy trades emissions (rights) off against tax revenues. Therefore, levying an emissions tax higher than the marginal damage is akin to pricing emissions above marginal cost. Such an emissions pricing generates social inefficiency.[8]

Next, turning to the abatement side, remark that as noted above, in the case of abatement technology transfer the polluters optimally reduce their emissions up to the point where the marginal cost of abatement is equal to the emissions tax. By doing so they realize some gains on infra-marginal abatement units. Part of these gains, however, returns to the technology supplier through the payment of licensing fees. The optimal emissions tax therefore results from a trade-off between efficiency and *rent-shifting* motives. Lowering the emissions tax below the Pigouvian level potentially accomplishes two beneficial operations. First, it alleviates the tax burden imposed on polluters and somehow passed on to consumers. This benefits society provided that the social marginal value of the good exceeds its social marginal cost. Second and in the case of international technology transfer, lowering the tax reduces the technology suppliers' pie and thereby reduces the outflow of licensing fees.

Finally, observe that when the polluting industry is perfectly competitive, there is no distortion *at the*

[8]Since the social marginal cost of emissions is equal to the marginal damage of emissions, when the polluting industry is imperfectly competitive, levying an emissions tax higher than this marginal damage thus causes a double marginalization problem.

margin if the emissions tax is equal to the marginal damage. Therefore, when all the proceeds of licensing are recouped domestically, there is no need to depart from the Pigouvian rule.

The remainder of the paper is organized as follows. The model is described in the next section. The second-best emissions tax is derived in Section 3 and Section 4 contains concluding remarks.

2 Model

The basic model features an international eco-industry supplying *end-of-pipe* abatement technologies to a polluting industry. In this latter industry, n symmetric producers compete à la Cournot to supply a homogenous good market characterized by the inverse demand $P(Q)$, where Q denotes the industry aggregate output and $P'(Q) < 0$ for all $Q > 0$. The production costs function $C(q)$ is strictly increasing, strictly convex and such that $C(0) = 0$ and $C'(0) = 0$. Moreover, the production process generates by-product emissions of a harmful pollutant and *polluters* are subject to a per unit emissions tax t.

To reduce their emissions, the polluters can implement a patented *end-of-pipe* abatement technology allowing to remove part of the pollution generated during their production process. Equipped with such technology, a polluter producing q units of the polluting good and a units of abatement would release only $e(q, a)$ units of emissions into the environment and would accordingly pay an amount of emissions taxes equal to only $te(q, a)$. The positive pollution function $e(q, a)$ is assumed to be twice continuously differentiable, strictly increasing and convex in q. Producing more abatement reduces emissions but with decreasing returns. Thus, $e(q, a)$ is strictly decreasing and strictly convex in a. Moreover, to capture the *end-of-pipe* characteristic of abatement, it is furthermore assumed that $e_{qa}(q, a) = 0$. This last assumption in fact implies that the pollution function is separable in q and a. Hence, let us write $e(q, a) = \max\{0, v(q) - w(a)\}$ with $v'(q) > 0$, $v''(q) \leq 0$, $w'(a) > 0$ and $w''(a) < 0$ for all $q > 0$ and all $a > 0$. The cost of producing a units of abatement is $G(a)$ where $G(\cdot)$ is a strictly increasing and strictly convex function.

The polluters adopting this technology must pay fixed license fees to a (representative) technology supplier whose licensing revenues are potentially shared among national and foreign owners. International competition within the eco-industry is modeled in a reduced form. It is simply assumed that a share $f \in [0,1]$ of the eco-industry's profits ends up on foreign account. For simplicity, assume that there are no costs of transferring and installing the technology. Moreover, to facilitate the analysis, the following three reasonable assumptions are maintained throughout the paper.

Assumption 1 *$P(Q)$ is twice continuously differentiable and $-P''(Q)Q/P'(Q) > -(n+1)$ for all $Q > 0$.*

This common assumption requiring that the demand function be not too concave ensures existence and uniqueness of the Cournot equilibrium (see e.g., Novshek (1985)).

Assumption 2 *The function $G(\cdot)$ satisfies $G(0) = 0$ for all $a > 0$ and $G'(a) > 0$ and $G''(a) > 0$*

Hence, there are no fixed costs and some abatement is always profitable whenever $t > 0$.

Assumption 3 *$t < \lim_{q->0} P(q)$.*

In words, the regulation is assumed not to be "too stringent" so that, even in the absence of abatement, producing the polluting good is profitable. Assumption 3 guarantees that every polluter's output and emissions levels are strictly positive in equilibrium thus allows one to restrict attention only to interior equilibria.

3 The Pigouvian tax rule and international technology transfer

Suppose that the n polluters implement the end-of-pipe technology. Faced with an emissions tax t, taking as given the output of its competitors, Q_{-q}, each polluter would solve

$$\max_{q,a} \pi_a(q,a) = P(Q_{-q} + q)q - C(q) - G(a) - t\left[v(q) - w(a)\right]$$

Let $\frac{Q^t}{n}$ and a^t denote respectively the symmetric equilibrium individual production and abatement levels. The necessary and sufficient first-order conditions with respect to q and a (at an interior solution) are then respectively[9]

$$P'(Q^t)\frac{Q^t}{n} + P(Q^t) - C'(\frac{Q^t}{n}) - tv'(\frac{Q^t}{n}) = 0 \quad (1)$$

$$tw'(a^t) - G'(a^t) = 0 \quad (2)$$

Each polluter chooses its output level as if it were operating along the marginal cost curve $C'(q) + tv'(q)$ (i.e. just as if it were not implementing the abatement technology). Moreover, as condition (2) indicates, each polluter equipped with the end-of-pipe abatement technology will pursue abatement up to the point, a^t, where the marginal return of abatement, $\tau w'(a^t)$, is equal to the marginal cost of abatement, $G'(a^t)$.

Now, let π_a^t and π_0^t denote respectively the equilibrium profit actually gained by a polluter implementing the patented abatement technology (gross of licensing fees) and that it would have realized without this technology. In this latter case, the pollution function would have been $e(q, 0) = v(q)$. Hence, $\pi_a^t = P(Q^t)\frac{Q^t}{n} - C(\frac{Q^t}{n}) - t\left[v(\frac{Q^t}{n}) - w(a^t)\right] - G(a^t)$, while $\pi_0^t = P(Q^t)\frac{Q^t}{n} - C(\frac{Q^t}{n}) - tv(\frac{Q^t}{n})$. The (gross) private gains of implementing the patented abatement technology are given by the difference between these profits, which (given that $G'(0) = 0$) can be written as

$$\pi_a^t - \pi_0^t = \int_0^{a^t} [tw'(a) - G'(a)]\, da \quad (3)$$

In words, these gains (which provide an upper bound on the licensing revenues that can be extracted from each polluter) are just the benefits realized on infra-marginal abatement units. Next, abstracting away from the subtlety of the licensing game, let $f \in [0, 1]$ denote the share of imported technology, that is, the share of licensing revenues "leaking" outside the boundaries of the domestic economy. The polluting industry's net domestic profit is thus given by $n\,[\pi_0^t + (1 - f)(\pi_a^t - \pi_0^t)]$.

Welfare in the case of international technology transfer. Social welfare is the sum of consumer surplus, the domestic polluters' profits, the emissions taxes revenues, minus the environmental damage.

[9] Throughout the paper it is assumed that $v(\frac{Q^t}{n}) - w(a^t) > 0$.

Then, assuming that the n polluters implement the patented abatement technology and using expression (3), domestic social welfare, expressed as a function of t can be written

$$W^t = \int_0^{Q^t} P(u)du - nC(\frac{Q^t}{n}) - ntv(\frac{Q^t}{n}) + n(1-f)\int_0^{a^t} [tw'(a) - G'(a)]\,da + tE^t - D(E^t) \tag{4}$$

Making use of the first-order condition (2), total differentiation of this expression with respect to t yields after simplification (see Appendix)

$$\frac{dW^t}{dt} = \frac{dQ^t}{dt}\left[P(Q^t) - C'(\frac{Q^t}{n}) - tv'(\frac{Q^t}{n})\right] - nv(\frac{Q^t}{n}) + n(1-f)w(a^t) + E^t + \frac{dE^t}{dt}(t - D'(E^t)) \tag{5}$$

Next, recalling that $E^t = nv(\frac{Q^t}{n}) - nw(a^t)$ and making use of the first-order condition (1) yields the following necessary and sufficient first-order condition for welfare maximization (see Appendix)

$$\frac{dW^t}{dt} = \frac{1}{n\epsilon(Q^t)}P(Q^t)\frac{dQ^t}{dt} - nfw(a^t) + \frac{dE^t}{dt}\left(t - D'(E^t)\right) = 0 \tag{6}$$

The welfare effect of a marginal increase of the emissions tax can be decomposed as follows. The first and last terms of the right-hand side of equation (5) capture respectively, the forgone social surplus due to a marginal reduction of aggregate production of the polluting good and the social benefits (resp. losses) if $t > E^t$ (resp. if $t < E^t$) arising from a marginal reduction of the aggregate emissions level. Next, the term $-nfw(a^t)$ represents the "leakage" of emissions tax revenues, accruing to foreign technology suppliers. Then, investigating the sign of the total derivative of W^t with respect to t, evaluated at $t = D'(E^t)$ helps determine how the welfare-maximizing emissions tax t^* compares with the marginal damage of emissions $D'(E^{t^*})$.

As shown in Figure 1, by the strict concavity of the welfare function, a positive (resp. negative) sign would imply that the second-best emissions tax is higher (resp. lower) than the marginal damage of emissions. Hence, the next proposition follows.

Proposition 1 *In the case of technology transfer, the second-best emissions tax never exceeds the marginal* *damage of emissions and decreases as the share of imported technology increases. When the polluting industry is imperfectly competitive, this tax is* always *lower than the Pigouvian level (i.e. for all $f \in [0,1]$). In contrast, when the polluting industry is competitive, the second-best emissions tax is lower than the marginal damage of emissions* only *in the case of* incoming *international technology transfer (i.e. iff $f > 0$). If the technology is transferred domestically (i.e. if $f = 0$), then the second-best emissions tax is equal to the marginal damage.*

Proof. For all $f > 0$, equation (6) immediately yields $\frac{d^2W^t}{dtdf} = -nw(a^t) < 0$ whenever $a^t > 0$. Hence the function W^t is strictly submodular in (t, f) and the by the monotone comparative statics theorem, $\frac{dt^*(f)}{df} < 0$. Moreover,

$$\frac{dW^t}{dt}|_{t=D'(E^t)} = \frac{1}{n\epsilon(Q^t)}P(Q^t)\frac{dQ^t}{dt} - fnw(a^t) \leq 0$$

where the last inequality holds strictly except for $f = 0$ when $\epsilon(Q^t) \to \infty$. ■

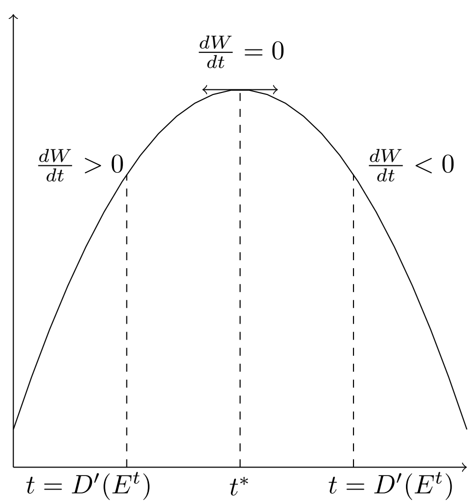

Figure 1: Welfare as a function of t.

In contrast to the over-internalization prescription of David and Sinclair-Desgagné (2005), when the abatement technology is transferred to the polluters, *at the margin*, no distortion needs to be corrected by an emissions tax in excess or short of the Pigouvian level. Hence, the only reason for departing from the

Pigouvian tax rule is to be found below the margin. When devising on the appropriate emissions tax level, the government weighs the surpluses domestic consumers and polluters. Since the oligopoly rents accruing to the eco-industry are shared between domestic and foreign EGS suppliers, the second-best emissions tax results from a trade-off between productive efficiency and international *rent-shifting* motives. Indeed, levying an emissions tax higher than the marginal damage amounts to an "implicit" subsidy granted by the government to the international eco-industry at the expense of its domestic consumers and polluters. Such a subsidy is costly to society since pricing emissions above their marginal cost entails a deadweight loss.

Lowering the emissions tax below the Pigouvian level thus potentially accomplishes two beneficial operations. First, it alleviates the tax burden imposed on domestic polluters and somehow passed on to consumers. Second, in the case of international trade of EGS, it reduces the outflow of abatement expenditures. Therefore, when all the proceeds of licensing are recouped domestically (i.e. when $f = 0$), there is no need to depart from the Pigouvian tax rule. In contrast, whenever part of these proceeds ends up on foreign account (i.e. when $f > 0$), *it is economically sound to lower the emissions tax below the Pigouvian level so as to reduce the outflow of licensing fees.*

Finally, observe furthermore that when the eco-industry is competitive, the unit price of EGS is equal to their marginal cost. Hence, the following proposition obtains as a corollary of Proposition 1

Proposition 2 *In the absence of market power in both the eco-industry and the polluting industry, the welfare-maximizing emissions tax is lower than the marginal damage of emissions whenever some EGS are imported.*

As this proposition indicates, even in the absence of distortions due to the exercise of market power in either industry, the emissions tax-induced international redistribution of rents might call for departing from the Pigouvian tax rule. This, however, should not be readily interpreted as attempts to manipulate environmental policies since, as recalled in Barrett (1994) from (GATT, 1992, p. 29):

> The existence of less strict environmental standards in a lower income country... is not a sufficient basis for claiming that the environmental standards are too low or that the country is manipulating its environmental standards in order to improve the competitiveness of its producers. To substantiate such

a claim, it would be necessary at the very least to demonstrate that the standards are even lower than would be expected on the basis of such factors as the level of per capita income and the characteristics of the physical environment.

It's all right. But then, environmental goods and services suppliers' competitive environment matters too.

4 Concluding remarks

We have investigated the impact of international technology transfer on optimal pollution taxation. Our analysis reveals that the second-best emissions tax results from a trade-off between productive efficiency and *rent-shifting* motives. In line with the well-known fact that governments whose polluters rely on imported abatement technologies are less inclined to enforce stringent environmental policies, the second-best emissions tax decreases as share of imported technologies increases. When the polluting industry is imperfectly competitive, this tax is *always* lower than the marginal damage. In contrast, when the polluting industry is perfectly competitive, the second-best emissions tax is lower than the marginal damage only in the case of *incoming* technology transfer. If the technology is transferred domestically, the second-best emissions tax is equal to the marginal damage.

The impact of market power in the *environmental goods and services industry* or the *eco-industry* on optimal policy design is drawing a growing attention from academics and policymakers alike. By definition, patents endow technology suppliers with some monopoly power. However, these results contrast with the literature on the impact of market power in the eco-industry on optimal policy design initiated by David and Sinclair-Desgagné (2005). This literature focuses on end-of-pipe environmental goods and *services* such as waste management services subject to linear pricing. Instead, the present work shifts the focus on *environmental equipment* such as end-of-pipe pollution abatement *technologies* (as opposed to abatement *services*). This note thus contributes to this literature by extending the analysis to the case of abatement technologies with the possibility of international technology transfer.

5 Appendix

Comparative statics Total differentiation of the first-order condition (2) w.r.t. t yields

$$\frac{dQ^t}{dt} = \frac{nv'(\frac{Q^t}{n})}{P''(Q^t)Q^t + (n+1)P'(Q^t) - C''(\frac{Q^t}{n}) - tv''(\frac{Q^t}{n})}$$

which is negative since $C'' > 0$, $v'' > 0$, $v'' > 0$ and in virtue of Assumption 1, $P''(Q^t)Q^t + (n+1)P'(Q^t) < 0$.

Total differentiation of the first-order condition (2) w.r.t. t yields

$$\frac{da^t}{dt} = -\frac{w'(a^t)}{tw''(a^t) - G''(a^t)}.$$

which is positive for all $t > 0$, since $w' > 0$, $w'' < 0$, $G'' > 0$.

$$\frac{dE^t}{dt} = \frac{dQ^t}{dt} - n\frac{da^t}{dt} > 0.$$

Derivation of equation (6) Starting from equation (4)

$$W^t = \int_0^{Q^t} P(u)du - nC(\frac{Q^t}{n}) - ntv(\frac{Q^t}{n}) + n(1-f)\int_0^{a^t} [tw'(a) - G'(a)]\,da + tE^t - D(E^t)$$

note first that total differentiation of $\int_0^{a^t} [tw'(a) - G'(a)]\,da$ w.r.t t immediately yields (by Leibniz's rule)

$$\frac{da^t}{dt}\left[tw'(a^t) - G'(a^t)\right] + w'(a^t) = w'(a^t)$$

by virtue of the first-order condition (2). Thus, totally differentiating equation (4) yields equation (5)

$$\frac{dW^t}{dt} = \frac{dQ^t}{dt}\left[P(Q^t) - C'(\frac{Q^t}{n}) - tv'(\frac{Q^t}{n})\right] - nv(\frac{Q^t}{n}) + n(1-f)w(a^t) + E^t + \frac{dE^t}{dt}(t - D'(E^t))$$

Rearranging terms then gives

$$\frac{dW^t}{dt} = \frac{dQ^t}{dt}\left[P(Q^t) - C'(\frac{Q^t}{n}) - tv'(\frac{Q^t}{n})\right] - n\left[v(\frac{Q^t}{n}) - nw(a^t)\right] - nfw(a^t) + E^t + \frac{dE^t}{dt}(t - D'(E^t))$$

Then, since the first-order condition (1) yields

$$\frac{P(Q^t) - C'(\frac{Q^t}{n}) - tv'(\frac{Q^t}{n})}{P(Q^t)} = \frac{1}{n\epsilon Q^t}$$

noting that $n\left[v(\frac{Q^t}{n}) - nw(a^t)\right] = E^t$ gives expression (6).

References

Barnett, A. H. (1980). The pigouvian tax rule under monopoly. *The American Economic Review*, 70(5):pp. 1037–1041.

Barrett, S. (1994). Strategic environmental policy and intrenational trade. *Journal of Public Economics*, 54(3):325–338.

Buchanan, J. M. (1969). External diseconomies, corrective taxes, and market structure. *The American Economic Review*, 59(1):174–177.

Canton, J., Soubeyran, A., and Stahn, H. (2008). Environmental taxation and vertical cournot oligopolies: How eco-industries matter. *Environmental and Resource Economics*, 40(3):369–382–382.

David, M. and Sinclair-Desgagné, B. (2005). Environmental regulation and the eco-industry. *Journal of Regulatory Economics*, 28(2):141–155.

David, M. and Sinclair-Desgagné, B. (2010). Pollution abatement subsidies and the eco-industry. *Environmental and Resource Economics*, 45(2):271–282–282.

Greaker, M. and Rosendahl, K. E. (2008). Environmental policy with upstream pollution abatement technology firms. *Journal of Environmental Economics and Management*, 56(3):246–259.

Hamilton, S. F. and Requate, T. (2004). Vertical structure and strategic environmental trade policy. *Journal of Environmental Economics and Management*, 47(2):260–269.

Martinez-Fernandez, C., Hinojosa, C., and Miranda, G. (2010). Green jobs and skills: the local labour market implications of addressing climate change. *OECD*, Working document, CFE/LEED.

Muller, N. Z. and Mendelsohn, R. (2007). Measuring the damages of air pollution in the united states. *Journal of Environmental Economics and Management*, 54(1):1 – 14.

Nimubona, A.-D. and Sinclair-Desgagné, B. (2013). The pigouvian tax rule in the presence of an eco-industry. *Economics Bulletin*, 33(1):747–752.

Novshek, W. (1985). On the existence of cournot equilibrium. *Review of Economic Studies*, 52(1):85–98.

OECD (2001). Environmental goods and services: The benefits of further global trade liberalisation. *OECD Policy Brief, OECD Paris.*

Perino, G. (2010). Technology diffusion with market power in the upstream industry. *Environmental and Resource Economics*, 46(4):403–428.